LCA Case Studies

Environmental Assessment of Brownfield Rehabilitation Using Two Different Life Cycle Inventory Models

Part 2: Case Study

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Environmental Assessment of Brownfield Rehabilitation Using Two Different Life Cycle Inventory Models
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Preamble. Brownfield rehabilitation recycles land resources in an open loop. LCA has been used in the past to evaluate the reduction in site-specific impacts and the impacts of the rehabilitation service system itself, called primary and secondary impacts in this paper, respectively. The consequences of reintroducing the site in the economy have not, however, been considered. This last has been touted as an efficient way to counter environmentally destructive urban sprawl. This article is the first of two on how a consequential model allows the inclusion of the environmental consequences of reoccupying a brownfield, called tertiary impacts in this paper. The second paper provides an actual case study.

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Abstract

Goal, Scope and Background. The principal aim of this paper is to evaluate the environmental attributes and consequences of a 'rehabilitation for residential redevelopment' scenario. It is contrasted to a non-intensive and low-cost 'exposure minimization' scenario, assumed to be the default intervention option to obtain compliance. This paper also aims to (1) quantitatively evaluate the relative environmental significance of primary, secondary and tertiary impacts, and (2) to compare conclusions obtained from attributional and from consequential LCA of the same decision.

Main Features. An attributional LCA (ALCA) and a consequential LCA (CLCA) are used to compare the two radically different intervention options. The rehabilitation for residential redevelopment scenario involves 'dig and dump' remediation, infrastructure material recycling and site backfilling. The 'exposure minimization' scenario consists in covering the site with clean soil and subsequently idling the site. The functional unit allowing this comparison is the 'legal and appropriate intervention on 1 ha of the tracked brownfield'. The inventory analyses are done following the proposals in Part 1. The LCIA is done using IMPACT 2002+ method.

Results and Conclusions. The ALCA results show no clear preference for either intervention option because of the trade-off between the benefits of decontamination and the impacts of the rehabilitation service system. The CLCA, on the other hand, unequivocally supports rehabilitation if it is followed by residential reuse, as long as the development of suburban sites is avoided. In these cases, tertiary environmental benefits dominate other types of impacts. It is concluded that, when brownfield intervention decisions can affect the fate of the site, the scope of brownfield management LCA should always be expanded to account for tertiary impacts.

Perspectives. The methodology proposed was restricted to a single site and to residential redevelopment. It is suggested that the general approach could be used for other types of brownfield redevelopments and for decisions affecting multiple brownfields.

Keywords: Attributional LCA (ALCA); Brownfield; Brownfield rehabilitation; consequential LCA (CLCA); contaminated site remediation; open-loop recycling

1 Introduction

1.1 Background

Brownfields are sites that have in the past been host to human occupation, are vacant or underutilized and can only be reused if they are first rehabilitated. Brownfields are also commonly contaminated, often contain redundant or decrepit infrastructure and are principally found in urban contexts [1,2]. Brownfield rehabilitation is actively promoted in many countries in order to counter environmental, social and economic problems associated to their physical state and the fact that they are idle.

Part 1 to this article [3] distinguishes between three types of environmental aspects associated with brownfield rehabilitation: primary impacts, associated to the changes in the site's environmental quality; secondary impacts, caused by the rehabilitation service system; and tertiary impacts, associated with effects of the reoccupation of the site on the life cycles of other regional sites. Part 1 also generically compares the use of attributional and consequential LCA (ALCA and CLCA) to evaluate these environmental aspects. Both approaches allow the inclusion of primary and secondary impacts, although models may differ slightly. Tertiary im-

pacts are included in the CLCA only. The CLCA scope is much larger than that of the ALCA, and is associated with important sources of uncertainty.

1.2 Aim

The principal aim of the paper is to use both the attributional and consequential methodologies proposed in Part 1 to evaluate the potential environmental impacts associated with a brownfield rehabilitation project aiming at residential redevelopment. This paper also aims to answer the following questions:

- What conclusions can be arrived at about the use of CLCA rather than ALCA for comparing brownfield intervention options that do not result in the same site fate?
- What is the relative significance of primary, secondary and tertiary impacts of brownfield rehabilitations aimed at residential redevelopment?

These will be answered in reference to a case study, presented below. The decision this study should support has already been taken, and rehabilitation has already occurred. Also, the questions do not require the results to be precise, but rather simply indicate what aspects should be considered seriously in future rehabilitation LCA that aim to support actual decisions. Data requirements are therefore not strict, although sensitive parameters and major sources of uncertainty should be identified.

2 Case Study Presentation

2.1 Context

The case consists of the rehabilitation of a 50.5 ha brownfield in the Montreal (Canada) urban core. The site had hosted heavy industrial activity in the railroad sector for nearly a century, which had left a legacy of soil contamination, lenses of potentially hazardous slag and standing and in-ground obsolete or redundant infrastructure.

The applicable environmental legislation in the Province of Quebec [4] initially determines the suitability of a site for redevelopment using generic risk criteria: criterion B, below which any type of development is possible, and criterion C, below which commercial and industrial development is allowed. An average hectare in the portion of the site under analysis contained 1,656 m^3 of soil above criterion C (>C soil) and 4,616 m^3 between criteria B and C (BC soil). **Table 1** presents the aggregated average concentrations of three types of contaminants: petroleum hydrocarbons (PHC), metals and polycyclic aromatic hydrocarbons (PAH). A quantitative risk assessment [5] concluded that the contaminants posed an unacceptable risk to human health, even if the site were left idle, implying some sort of intervention was needed.

After idling for five years, a vast rehabilitation project was undertaken on the brownfield in the late 1990's [6, 7]. The project consisted of rehabilitation for residential (23.1 ha), commercial (3.8 ha) and recreational (2.7 ha) redevelopment. A small section of the site (2.0 ha) was used for onsite confinement of slag and contaminated soil. The rest of the site (18.9 ha) was subject to a minimal risk management strategy (exposure minimisation) and may be reused for industrial development pending a prerequisite risk assessment and potentially rehabilitation. The object of analysis in this paper is the rehabilitation for residential redevelopment (BR), and exposure minimisation (EM) is assumed to be the default intervention option.

2.2 Option 1: Brownfield rehabilitation for residential redevelopment (BR)

The brownfield rehabilitation option (BR) consisted of three types of activities: (1) risk management through excavation and disposal of contaminated soils and wastes (dig and haul); (2) infrastructure demolition and recycling of recoverable materials; and (3) landscaping (site backfilling). The rehabilitation took place over a period of approximately two years.

Dig and haul. Contaminated soil, slag and dry solid waste were excavated, temporarily stored onsite and characterized. The fate of the excavated soils depended on their contamination level: <B soil was reused onsite as backfill; BC soil was landfilled offsite; and >C soil was confined in onsite and offsite containment cells. Slag qualifying as solid waste was landfilled offsite, and that qualifying as 'special waste' was confined in onsite containment cells. Dry solid wastes were landfilled. Other activities included pumping and management of water accumulating in excavation cells, environmental monitoring and dust mitigation.

Infrastructure management. The activities included the removal of recoverable cement and bituminous concrete from onsite infrastructure followed by primary and secondary crushing. The resulting aggregates were then reused or sold on the market. Other recovered materials (e.g., metal and wood from railways) were also recycled.

Table 1: Legacy soil contamination on brownfield at industrial occupation end-of-life

Contaminant class	Considered substances	Soil type	Concentration (ppm)
PHC [a]	C_{10}–C_{50}	BC	467
		>C	961
Metals	Arsenic, Baryum, Cadmium, Chromium, Cobalt, Copper, Lead, Mercury, Molybdenum, Nickel, Selenium, Zinc	BC	745
		>C	906
PAH [b]	Acenaphthylene, Acenaphthene, Anthracene, Benzo[a]anthracene, Dibenz[a,h]anthracene, Benzo[a]pyrene, Benzo (b+j+k)-fluoranthene, Benzo[g,h,i]perylene, Chrysene, 7,12-Dimethylbenz[a]anthracene, Fluoranthrene, Fluorene, Indeno[1,2,3-cd]pyrene, 3-Methylcholanthrene, Naphtalene, Phenanthrene, Pyrene	BC	29
		>C	154

[a] Petroleum hydrocarbons, measured as C_{10}-C_{50}
[b] Polycyclic aromatic hydrocarbons

Backfilling. The excavated site was backfilled to an elevation 53 cm lower than the original level. Three sources of soils were used: clean soil excavated as part of the dig and haul stage (closed-loop recycling), soil extracted from commercial pits (primary backfill) and soil generated from regional construction projects (secondary backfill).

2.3 Option 2: Exposure minimisation (EM)

The 'exposure minimisation for compliance' option (EM) aimed at reducing risk to acceptable levels by minimising exposure, and simply consisted of covering the site with 30 cm of clean soil. The amount of contamination on the site was not changed, and the site remained vacant (fate unchanged). The time needed for this option is estimated at 1 year.

3 Methods

3.1 Functional unit and reference flow definition

LCA is used here to evaluate the environmental impacts of choosing BR over EM as a brownfield intervention option. In the attributional approach, a distinct ALCA needs to be carried out for each option, and their respective results are compared. This requires a common functional unit, defined here as 'legal and appropriate management of legacy contamination on 1 ha of the tracked brownfield'. The reference flow is one hectare of the tracked brownfield. In the CLCA, only BR is subject to an LCA, and EM is within its scope as an avoided scenario. For consistency and easier comparison with the ALCA, the same functional unit and reference flow are used.

3.2 Scopes of studies

The attributional and consequential scopes of the LCA of brownfield management were generically discussed in detail in Part 1 [5]. For both brownfield intervention options, the ALCA scope is limited to the life cycle of intervention activities. The BR option exports a 'redevelopable land production' function, which is cut-off. Both primary and secondary impacts are considered. Two time horizons are specified: (1) one for technological processes, set equal to the duration of site processing activities (two years for BR and one year for EM) and (2) one for environmental processes, set sufficiently long for emissions of residual contamination on the brownfield to be pertinent. It is supposed that this second time horizon is too short for long-term emissions from landfills to be significant. This last hypothesis visibly enhances the primary benefits of BR.

The CLCA should account for processes that are affected by choosing BR over EM, either positively (incurred impacts) or negatively (avoided impacts). The CLCA scope differs from the ALCA scopes in four ways. First, the BR service system includes only actually affected activities [8]: constrained production factors and processes are excluded and replaced with the corresponding marginal technology, and functions exported from multi-functional processes are accounted for through system expansion. Second, the system boundaries are expanded to the subsequent site occupation life-cycle, by which the exported 'redevelopable land production' function is internalised. The exported function becomes that of the subsequent occupation, i.e. supply of housing services. Third, the system is further expanded to include other site occupations marginally affected by this increase in supply of housing services. These sites are all considered to be in the Montreal Metropolitan Area. Finally, the avoided EM option is included within the scope of the study. The time horizon for technological processes is shown in **Table 2**. It begins with the rehabilitation phase and extends to 40 years of occupation (total time horizon of 44 years). The time horizon for environmental processes is the same as in the ACLI.

3.3 LCIA method

The same LCIA method is used for both LCAs, namely IMPACT 2002+ (v2.0). This method has been described elsewhere [9]. The method provides characterisation factors for 15 midpoint and 4 damage (endpoint) categories. This paper will focus on endpoint indicators, i.e. damages to human health (HH), ecosystem quality (EQ), climate change

Table 2: Time distribution of incurred and avoided impacts for the CLCA

Incurred impacts (a, b)									
I	Land occupation during rehabilitation		Land occupation during redevelopment		Land occupation during residential occupation				
II	Rehabilitation service system								
III			Redevelopment of tracked site		Residential occupation of tracked site				
Avoided impacts (a, c)									
I (contamination)	Site contamination								.....
I (land occup.)	Land occupation during exposure minimisation	Land occupation as abandoned brownfield							
II	Exposure minimisation service system								
III			Redevelopment of affected sites		Occupation of affected sites				
Time (years)	0	1	2	3	4	14	24	34	44

(a) I=Primary impacts; II=Secondary impacts; III=Tertiary impacts
(b) Incurred impacts are positive
(c) Avoided impacts are negative

(CC) and resources (R), as well as on the land occupation midpoint category. The time horizon in the method is hypothetical infinite, sometimes approximated as 500 years, e.g. for global warming. Normalisation factors for damages were derived for Western Europe. Values for characterisation and normalisation factors are available on the EPFL website (http://www.epfl.ch/impact). No weighting set was developed in the context of this study, and normalised results are therefore not aggregated in a single score.

The relevance of the LCIA results is diminished since (1) a European LCIA methodology is used for a Canadian context, and (2) the method is based on the less-is-better approach, which, although well suited for ALCA, is less appropriate than an only-above-threshold approach for CLCA. Despite these problems, the used approach is considered sufficient for the aims of this study.

3.4 Inventory for primary impact assessment

Two types of primary impacts are considered: (1) those related to site contamination and (2) those related to the physical state of the site. These impacts are by definition site-specific: however, to facilitate the integration of primary impacts with other LCA results and to reduce assessment effort, simplified LCIA-based approaches are taken here. Ideal data sources are contrasted to actually used data in **Table 3**.

Site contamination: Assessing potential impacts of contaminants is drastically simplified by treating all residual soil contaminants above the 'B' criterion as 'emissions to soil' in the LCI. This type of approach has been used elsewhere in a site remediation LCA [10]. All contaminants are considered removed in the BR option, while all remain onsite for the EM option. The mass of soil contaminants was calculated from data supplied by the site owner [6,7].

This procedure introduces important uncertainty. First, it assumes that long-term emissions from the site can be treated in the same manner as present emissions from other processes. In these cases, the IMPACT 2002+ method suggests that long-term emissions should be presented distinctly from short-term emissions in the interpretation phase. Also, the contribution of these contaminants to the site's overall ecosystem quality is not marginal in the least, even if the use of generic characterisation factors supposes they are. The evaluation of ecotoxicity for metals is especially problematic: (1) LCIA models for metal ecotoxicity are intrinsically uncertain because of the great difficulty in evaluating speciation, bioavailability and bioconcentration and (2) the IMPACT 2002+ damage factors are for emission of metal ions, for which no data was available in this study. The mass of ions was assumed to be 1% of the total mass of metals. Finally, no characterisation factor was found to adequately represent PHC: pentane is used as a poor-quality proxy.

Physical state of the site: Ideally, site-specific measures of ecosystem quality (EQ) would be used to describe the burdens of site transformation and occupation, and would include data on affected life support functions (LSF) and biodiversity. However, IMPACT 2002+ does not account for land transformation and only considers effects on biodiversity. Also, to simplify data collection, the ecosystem

Table 3: Data used for inventory of burdens resulting in primary impacts

Impact type	ALCI		CLCI	
	Ideal data type	Actual data type	Ideal data type	Actual data type
Site contamination				
	Onsite contaminants resulting in exposure	Total mass of onsite soil contaminants [a]	Onsite contaminants resulting in exposure	Total mass of onsite soil contaminants (–)
Land occupation (life-cycle phase)				
Rehabilitation	Site-specific measures of species richness	CORINE land class 'construction site' [a]	Site-specific measures of species richness (+)	CORINE land-use type 'construction site'
Redevelopment	n/a	n/a	Site-specific measures of species richness (+)	CORINE land-use type 'construction site'
Reoccupation	n/a	n/a	Site-specific measures of species richness (+)	CORINE land-use type 'urban, continuously built'
Exposure minim.	Site-specific measures of species richness	CORINE land class 'construction site' [b]	Site-specific measures of species richness (–)	CORINE land-use type 'construction site'
Idling	n/a	n/a	Site-specific measures of species richness (–)	CORINE land-use type 'indust. area, vegetation'
Land transformation				
Rehabilitation	Site-specific measures of effects on renaturation potential	Excluded (not considered by LCIA method)	Site-specific measures of effects on renaturation potential	Excluded (not considered by LCIA method)
Redevelopment				
Reoccupation				
Exposure minim.				
Idling				

[a] and [b] in ALCI section refer to the two distinct options assessed
(+) and (–) in the CLCI section refer to whether the burdens are incurred or avoided, respectively, when evaluating the burdens of rehabilitation

quality of generic land types as defined by CORINE [11] are used here instead of site-specific data. Site processing phases are assumed to be adequately represented by the 'construction site' CORINE land class. For the CLCI model, the subsequent development and occupation phases are assumed to be appropriately represented by 2 years of occupation as a 'construction site' and 40 years of occupation as 'continuously built urban land', respectively. For EM, the subsequent idling of the site as a brownfield is represented by the 'vegetated industrial area' class, for a total of 44–1=43 years.

3.5 Primary data for secondary impacts assessment

Primary data refers here to information on site processing activities, types and output of machinery used, fate of all excavated materials and sources of imported materials. All primary data is derived from rehabilitation plans [6], post-rehabilitation reports [7] and from discussions with the rehabilitation subcontractor [12].

'Dig and haul' BR subsystem: The attributional and consequential approaches yielded identical models for this subsystem. For onsite activities, only heavy machinery use was included in the inventory. **Table 4** presents, for each type of excavated material, the total amounts of machine-hours required for site processing and the material's fate. The following activities were excluded from the model: pumping and management of water collection in excavation cells (relatively insignificant volume); environmental monitoring (usually considered negligible in site remediation LCA, see e.g. [10,13]); and dust mitigation (no data).

'Infrastructure management' BR subsystem: Only the recovery and recycling of cement and bituminous concrete are included: other recovered materials (wood, metals) are excluded due to lack of primary data. Site processing data, used in the ALCI and CLCI alike, are presented in **Table 5**. For the ALCI, the subsequent offsite transport and reuse in other product life cycles are cut off. For the CLCI, the recycling is assumed to displace an equivalent amount of crushed gravel production, as was done in other studies [14,15].

'Backfilling' BR subsystem: The onsite activities for this subsystem are modeled identically for the ALCI and the CLCI and consist of spreading and compacting a total of 9,236 m^3 of clean soil (92.4 machine-hr for each activity). The modeled sources of backfill soil differ, however (**Table 6**). For the ALCI, actual sources are modeled: <B soil from the site excavation subsystem (0.1%), primary backfill from commercial soil pits (23.9%) and secondary backfill from construction projects (76%). The actual excavation of secondary backfill was allocated to the construction project from which it originated. For the CLCI, secondary backfill is considered a constrained resource and all soil acquired offsite is considered to come from commercial soil pits.

Avoided EM option: EM consists of the same activities as the backfilling subsystem: only the soil volume changes (3,000 m^3). Onsite activities again consist of spreading and compacting, both for 30 machine-hr. The backfill source is considered to be secondary for the ALCA and primary for the CLCA.

Table 6: Backfill used for ALCI and CLCI models

Backfill type	Distance from source (km)	Total for ALCI (m^3)	Total for CLCI (m^3)
Recycled soil from onsite excavation	0	172.2	172.2
Primary backfill from soil pits	31.2	2,175.9	9,064.2
Secondary backfill from regional construction sites	7.4	6,888.3	0

Table 4: Primary data for dig and haul subsystem (common for ALCI and CLCI)

Excavated materials		Onsite processes				Offsite processes	
Type	Volume (m^3)	Excavation (machine-hr)	Loading (machine-hr)	Onsite transport (machine-hr)	Sifting (machine-hr)	Fate	Avg. dist. (km)
<B soil	172.2	1.0	2.2	1.1	0.8	Onsite reuse (backfill)	n/a
BC soil	4,615.9	25.6	58.3	29.2	21.0	Offsite landfilling (inert)	37.0
>C soil	1,168.6	6.5	14.8	7.4	5.3	Offsite containment	52.1
>C soil	1,487.0	8.3	18.8	18.8	6.8	Onsite containment	n/a
Slag (solid waste)	2,860.9	15.9	27.2	18.1	0	Offsite landfilling (inert)	16.1
Slag (special waste)	119.2	0.7	1.1	1.5	0	Onsite containment	n/a
Dry solid wastes	927.2	5.1	11.8	5.9	4.2	Offsite landfilling (inert)	24.8

Table 5: Primary data for the infrastructure material recovery subsystem

Recovered material		Onsite activities					Avoided activities (CLCI)
Type	Volume (m^3)	Removal (machine-hr)	Loading (machine-hr)	Onsite transport (machine-hr)	Primary crushing (machine-hr)	Secondary crushing (machine-hr)	Aggregate production (m^3)
Cement concrete	2847.7	47.5	27.0	18.0	35.6	35.6	2847.7
Bituminous concrete	337.7	5.6	3.2	2.1	5.1	5.1	337.7

3.6 Primary data for tertiary impacts assessment

Quantifying effects on other sites: The redevelopment of the tracked site resulted in 84.8 attached single-family residences per ha. As stated in Part 1, this is considered to result in an equal number of single-family residences not being constructed on other sites in the region. Three distinct ratios of suburban and urban avoided constructions are assessed, as presented in **Table 7**. A 'best-case' scenario assumes that only suburban greenfields are affected, reflecting the assumption made in brownfield management and urban planning policy concerning the Montreal Metropolitan Area [16–18]. The 'most probable' scenario is based on an economic partial-equilibrium model and is explained at length in Part 1. A 'worst case' scenario, whereby only urban sites are considered affected, is also included for sensitivity check.

Data for modeling of developments and occupations: Data were collected for processes differing significantly for residential developments on the tracked and affected sites. Three aspects are considered: (1) the construction and/or maintenance of public infrastructure; (2) the energy requirements of the residences; and (3) car transport to and from residences by their inhabitants (**Table 8**). Relevant but nonetheless excluded processes included house construction, maintenance and end-of-life dismantling.

Table 7: Allocation scenarios for avoided constructions

Scenario	% effect		Notes
	Suburban greenfields	Urban vacant sites	
Best case	100%	0%	Common assumption in brownfield literature
Most probable	17.8%	82.2%	Based on partial-equilibrium model
Worst case	0%	100%	Extreme case for sensitivity check

Housing density: The housing density on the tracked site was directly measured from maps of the projected redeveloped site, and that of affected urban sites is assumed equivalent. The areal differential *AD*, measuring the difference of land use efficiency between urban and suburban housing, is set at 5.57, an estimate of the North America average *AD* for residential developments [19].

Housing type and description: Construction statistics for the Montreal Metropolitan Area between 1996 and 2001 [20, 21] showed that single-family residences in the urban area were predominantly attached dwellings (50%), while those in the surrounding land were detached dwellings (80%). Data on average floor space and energy use per dwelling type were obtained on the provincial level [22]. Heating is assumed to be supplied by electrical baseboards. The marginal electricity generation is assumed to be hydropower, which is the privileged option in Quebec [24].

Average travel distances: We account for recurrently traveled distances on workdays by residents of the affected sites, such as trips to and from workplace and school. The impacts of increased congestion, which is a known phenomenon in the Montreal region [25], are excluded. The estimation of distances is based on (1) an Origin-Destination (OD) study for 100 municipalities in the Montreal Metropolitan Area [23] and (2) on distance estimates generated by a Montreal traffic simulation model [26], provided by the Quebec Ministry of Transport [27]. The average vehicle distances for the urban and suburban areas were obtained by weighting the municipal-scale OD data by the number of new single-family dwellings built between 1996 and 2001 [20,21]. The number of workdays per year is set at 240.

Public infrastructure: Four types of onsite infrastructure are considered, all of which are linear: potable water and electricity distribution networks, roads and sewers. The length of roads on the tracked site was measured on a map, and all

Table 8: Primary data for tertiary impact LCI

Parameter	Unit	Incurred	Avoided		References
		Tracked site	Suburban site	Urban site	
Site type	n/a	Brownfield	Greenfield	Redevelopable vacant	Assumption
Conditional transformation phase	n/a	Rehabilitation	Land clearing (excluded)	None	n/a
Housing density	res/ha	84.8	15.2	84.8	Tracked: measured [7] Urban: assumed Suburban: estimated [19]
Single family residence type	n/a	Attached	Detached	Attached	[10,21]
Size of single family residence	m^2	121.3	149.7	121.3	[22]
Energy requirement – Heating	GJ/residence/yr	61.0	83.0	61.0	[22]
Energy requirement – Cooling	GJ/residence/yr	2.8	3.4	2.7	[22]
Energy requirement – Lighting	GJ/residence/yr	5.3	6.6	5.4	[22]
Average car distance	vkm/residence/workday	7.4	33.1	9.4	Dist. per municipality: [23] Weighting: [20,21]
Length of linear public infrastructure	m	161	380	161	Tracked: measured [7] Urban: assumed Suburban: estimated [19]

other linear infrastructures were assumed to be of the same length. The same lengths were used for infrastructure on other urban sites. For suburban sites, the lengths were estimated to be greater by a factor of $\sqrt{AD}$ =2.36. Because of data structure in the used database (see below), the construction of roads is attributed to the occupation phase and that of other public infrastructure to the development phase.

3.7 Secondary data sources for LCIs

Ideal and used inventory data sources are presented in **Table 9**. Most of the data used was average data from the European ecoinvent V1.2 database. Most emissions of heavy machinery operation were evaluated using US EPA's OFFROAD model [28], complemented with EEA's CORINAIR model for HAP and metal emissions [29].

4 Results and Interpretation

4.1 Primary impacts

Table 10 recapitulates inventory data for primary impacts and presents associated LCIA results for both the ALCA and the CLCA. Damage indicators show that the BR option is overall greatly beneficial for site-specific impacts, mainly due to the important human health and ecosystem quality damages of residual contaminants in the EM option. **Fig. 1** presents some detail on the impacts of residual contamination only. We can observe that, although PHC are the most representative contaminant class on a mass basis, they barely contribute to any impact category. This may be due to the low-quality proxy used in the LCIA method (pentane). PAH dominate human toxicity, while metal ions dominate ecotoxicity.

Table 9: Secondary data sources

Process name	ALCI		CLCI	
	Ideal data source	Actual data source	Ideal data source	Actual data source
Rehabilitation/Exposure minimisation phase				
Heavy machinery used onsite				
– Diesel consumption and operation emissions	Fleet-specific data	American average data [28] European average data [29]	Fleet-specific data	American average data [28] European average data [29]
– Lubricating oil consumption	Fleet-specific consumption data	ecoinvent 1.2: Lubricating oil at plant (European) [30]	Fleet-specific consumption data	ecoinvent 1.2: Lubricating oil at plant (European) [30]
– Machine manufacture	Fleet-specific data	ecoinvent 1.2: Building machine (European) [31]	Fleet-specific data	ecoinvent 1.2: Building machine (European) [31]
– Life expectancy	Fleet-specific data	American average data [28]	Fleet-specific data	American average data [28]
Offsite material transport	Transport fleet-specific data	ecoinvent 1.2: Lorry, 28 t (European) [32]	Transport fleet-specific data	ecoinvent 1.2: Lorry, 28 t (European) [32]
Landfilling (inert material)	Regional average	ecoinvent 1.2: Inert material landfill facility (Swiss) [33]	Regional marginal	ecoinvent 1.2: Inert material landfill facility (Swiss) [33]
Offsite containment	Regional average	ecoinvent 1.2: Slag compartment (Swiss) [33]	Regional marginal	ecoinvent 1.2: Slag compartment (Swiss) [33]
Onsite containment	Primary data	ecoinvent 1.2: Slag compartment (Swiss) [33]	Primary data	ecoinvent 1.2: Slag compartment (Swiss) [33]
Crushed gravel production	n/a	n/a	Regional marginal	Gravel, crushed, at mine (Swiss) [31]
Primary backfill production	Regional average	ecoinvent 1.2: Sand, at mine (Swiss) [31]	Regional marginal	ecoinvent 1.2: Sand, at mine (Swiss) [31]
Secondary backfill production	Excluded	Excluded	n/a	n/a
Diesel supply	Regional average	ecoinvent 1.2: Diesel, at regional storage (Swiss) [34]	Regional marginal	ecoinvent 1.2: Diesel, at regional storage (Swiss) [34]
Development and occupation phases				
Sewers	n/a	n/a	Regional average	ecoinvent 1.2. Residential sewer grid (Swiss) [33]
Potable water distribution network	n/a	n/a	Regional average	ecoinvent 1.2. Water supply network (Swiss) [30]
Electricity distribution network	n/a	n/a	Regional average	ecoinvent 1.2. Distribution network, electricity, low voltage (Swiss) [35]
Construction and maintenance of roads	n/a	n/a	Regional average	ecoinvent 1.2. Road (Swiss) [32]
Electricity production	n/a	n/a	Regional marginal	ecoinvent 1.2. Electricity, hydropower, at reservoir power plant, non-alpine regions (European) [36]
Car transportation to and from workplace	n/a	n/a	Regional average	ecoinvent 1.2. Transport, passenger car (Europe) [32]

Table 10: Summary of LCI and LCIA results for primary impacts

Indicator	[unit]	ALCA Rehabilitation (BR)	ALCA Exposure minimisation (EM)	CLCA Incurred	CLCA Avoided	CLCA Total
Inventory						
PHC to soil	[kg]	0	8.5E+3	0	8.5E+3	–8.5E+3
Metal ions to soil	[kg]	0	1.1E+2	0	1.1E+2	–1.1E+2
PAH to soil	[kg]	0	1.1E+3	0	1.1E+3	–1.1E+3
Occupation – Construction site	[m^2yr]	2.0E+4	1.0E+4	4.0E+4	1.0E+4	3.0E+4
Occupation – Urban, continuously built	[m^2yr]	0	0	4.0E+5	0.0E+0	4.0E+5
Occupation – Industrial site, vegetation	[m^2yr]	0	0	0	4.3E+5	–4.3E+5
Midpoint indicators						
Carcinogens	[kg_{eq} C_2H_3Cl]	0	9.2E+5	0	9.2E+5	–9.2E+5
Non-Carcinogens	[kg_{eq} C_2H_3Cl]	0	1.4E+5	0	1.4E+5	–1.4E+5
Aquatic ecotoxicity	[kg_{eq} $C_6H_{14}O_4$]	0	5.1E+8	0	5.1E+8	–5.1E+8
Terrestrial ecotoxicity	[kg_{eq} $C_6H_{14}O_4$]	0	3.6E+8	0	3.6E+8	–3.6E+8
Land use	[m^2yr_{eq} arable org.]	1.5E+4	7.7E+3	4.5E+5	3.4E+5	1.2E+5
Unweighted normalised damages						
Human Health	[pers*yr]	0	2.3E+2	0	2.3E+2	–2.3E+2
Ecosystem Quality (contamination)	[pers*yr]	0	2.1E+2	0	2.1E+2	–2.1E+2
Ecosystem Quality (occupation)	[pers*yr]	1.2E+0	6.1E-1	3.6E+1	2.7E+1	9.2E+0

It can also be observed in Table 10 that, for the CLCA, the primary impacts associated to the physical state of the site are positive, meaning that the future occupation of the site is more damaging to ecosystems for the BR option than for EM. However, these incurred primary impacts are one order of magnitude lower than the avoided impacts of contamination.

4.2 Secondary impacts

ALCA: The ALCI results for secondary impacts are presented in **Table 11**. To save space, only flows contributing to more than 2% to any of the damage categories are shown in this table. ALCI results for BR are all at least 29 times greater than those of EM, with even more dramatic differences for land occupation burdens. Attributional LCIA results are presented in the same table. The damages of BR are all between 34 and 43 times greater those of EM. Strictly on basis of secondary impacts, the conclusion is that EM is preferable, as was easily predictable.

For BR, the dig and haul subsystem is the most significant, making up at least 3/4 of the secondary impacts (damage level). The heavy burdens of landfilling and containing excavated materials are responsible for this dominance. Overall, these waste management processes represent about half of total secondary impacts (results not shown). Offsite transport of materials represents about 2/3 of the rest of the damages, with onsite activities and primary backfill acquisition making up the rest.

The fact that infrastructure management contributes much less than the two other BR subsystems seems to indicate that for ALCA this subsystem could be excluded, as is normally the case in remediation LCA. However, it should be noted that this conclusion stems from the fact that the offsite transport and management of removed infrastructure was excluded because of the chosen allocation procedure.

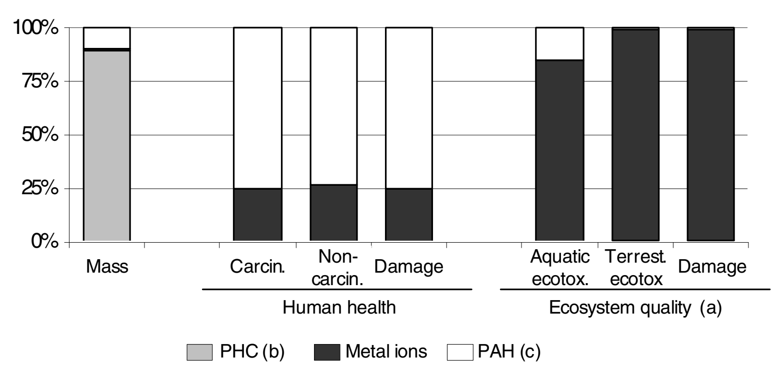


Fig. 1: Relative contributions of soil contaminant classes to primary impacts (ALCA and CLCA). (a) Damages to ecosystem quality only relate to soil contaminants and exclude damages of land use; (b) PHC: Petroleum hydrocarbons; (c) PAH: Polycyclic aromatic hydrocarbons

Table 11: Significant LCI and LCIA results for secondary impacts, ALCA

Elementary flows			**Associated damage categories [a]**				**Rehabilitation (BR)**				**Exposure minimisation (EM)**
Substance		**[unit]**	**HH**	**EQ**	**CC**	**R**	**Dig and haul**	**Infrastucture management**	**Backfilling**	**Total**	
Aluminum	Air	[kg]		X			3.2E+0	1.3E-1	1.0E+0	4.3E+0	1.3E-1
Aluminum	Soil	[kg]		X			2.1E+0	2.4E-1	3.6E-1	2.7E+0	6.4E-2
Aluminum	Water	[kg]		X			2.4E+1	1.4E+0	7.7E+0	3.3E+1	8.9E-1
Carbon dioxide, fossil	Air	[kg]			X		2.5E+5	2.7E+4	5.3E+4	3.3E+5	9.7E+3
Copper, ion	Water	[kg]		X			1.8E+0	2.3E-2	5.7E-1	2.4E+0	7.1E-2
Gas, natural, in ground	Raw	[m^3]				X	1.3E+4	6.1E+2	2.1E+3	1.5E+4	3.6E+2
Nitrogen oxides	Air	[kg]	X	X			2.2E+3	2.6E+2	4.4E+2	2.9E+3	8.3E+1
Occupation, dump site	Raw	[m^2yr]		X			1.4E+4	8.1E+0	5.5E+1	1.4E+4	5.9E+0
Occupation, mineral extraction site	Raw	[m^2yr]		X			6.4E+3	4.1E+0	1.2E+4	1.8E+4	6.0E+1
Occupation, traffic area, road network	Raw	[m^2yr]		X			9.0E+3	1.1E+1	1.9E+2	9.2E+3	9.6E+0
Oil, crude, in ground	Raw	[kg]				X	1.1E+5	8.1E+3	1.7E+4	1.4E+5	3.3E+3
Particulates, < 2.5 µm	Air	[kg]	X				1.5E+2	1.1E+1	2.7E+1	1.8E+2	4.5E+0
Particulates, > 10 µm	Air	[kg]	X				9.5E+1	3.2E+0	2.4E+1	1.2E+2	3.8E+0
Particulates, > 2.5 µm, and < 10 µm	Air	[kg]	X				4.7E+1	2.0E+0	1.2E+1	6.2E+1	1.9E+0
Sulfur dioxide	Air	[kg]	X				3.9E+2	3.9E+1	7.1E+1	5.0E+2	1.2E+1
Uranium	Air	[kg]				X	1.0E-5	6.8E-7	3.6E-6	1.4E-5	4.1E-7
Zinc	Air	[kg]		X			3.8E-1	7.2E-3	1.0E-1	4.9E-1	1.5E-2
Zinc	Soil	[kg]		X			8.6E-1	4.7E-3	2.0E-1	1.1E+0	3.6E-2
Normalised damages (pers*yr)											
Human Health (HH)							5.4E+1	5.0E+0	1.1E+1	6.9E+1	1.9E+0
Ecosystem Quality (EQ)							8.1E+0	2.9E-1	2.2E+0	1.1E+1	2.4E-1
Climate Change (CC)							2.6E+1	2.7E+0	5.5E+0	3.4E+1	1.0E+0
Resources (R)							3.8E+1	2.7E+0	6.4E+0	4.7E+1	1.1E+0

[a] HH=Human health, EQ=Ecosystem quality, CC=climate change, and R=Resources

CLCA. Significant CLCI results for the BR option are given in **Table 12** (cut-off 2% contribution to respective damage categories), as well as corresponding LCIA results. There is no difference between ALCA and CLCA results for the 'dig and haul' subsystem. The 'infrastructure management' subsystem is shown to be environmentally beneficial in the CLCA due to avoided aggregate production. This subsystem represents less than 5% of total incurred secondary impacts for all considered damages except for ecosystem quality, where it represents a little more than 15% due to the avoided occupation of mineral extraction sites. The impacts of the 'backfilling' subsystem and for 'EM' are both more important for the CLCA than for the ALCA, due to the exclusive use of primary backfill in the consequential model. The overall total of incurred and avoided impacts are all positive, again showing, strictly on a perspective of secondary impacts, that BR is worse than EM.

4.3 Tertiary impacts

Significant CLCI results of the development and occupation (on a yearly basis) of functionally equivalent residential developments on different sites are presented in **Table 13**. LCIA results are presented in **Table 14**, accounting for the total time of occupation (40 years). Damages are broken down in **Fig. 2**, showing that personal car transport of residents is dominant for all considered sites. The development phase is shown to be comparatively insignificant.

When comparing the residential developments amongst themselves, that on the tracked site shows the highest efficiency. When compared to avoided urban sites, this is due to shorter distances traveled by residents to and from workplace. Suburban developments are much less efficient, due mostly to much higher transport distances but also because of longer public infrastructures and less energy-efficient residences.

Tertiary impacts are ultimately calculated as the development and occupation impacts of the tracked site less that of the avoided urban or suburban sites. Given the LCIA results presented in Table 14, tertiary impacts will necessarily be negative (good for the environment), and the greater the share of avoided development assumed to be on suburban sites, the greater this environmental benefit will be.

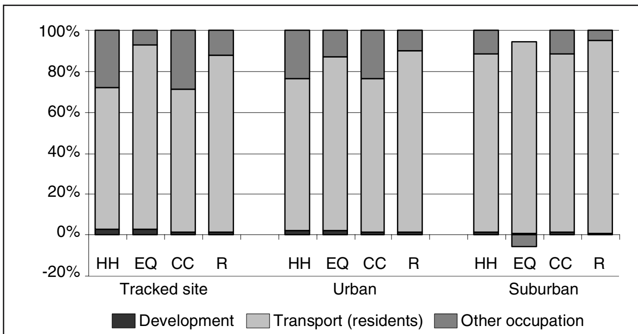
Table 12: Significant CLCI results for secondary impacts

Elementary flow		[Unit]	Associated damage categories [a]				Incurred			Avoided	Total
			HH	EQ	CC	R	Dig and haul	Infrastructure management	Backfilling	Exposure minimisation (EM)	
Aluminum	Air	[kg]		X			3.2E+0	–1.6E+0	2.9E+0	9.6E-1	3.5E+0
Aluminum	Water	[kg]		X			2.4E+1	–1.8E+1	2.4E+1	7.8E+0	2.1E+1
Aluminum	Soil	[kg]		X			2.1E+0	8.1E-2	8.8E-1	2.9E-1	2.8E+0
Carbon dioxide, fossil	Air	[kg]			X		2.5E+5	–4.4E+3	1.3E+5	4.2E+4	3.3E+5
Gas, natural, in ground	Raw	[m^3]				X	1.3E+4	–1.2E+3	5.1E+3	1.7E+3	1.5E+4
Nitrogen oxides	Air	[kg]	X	X			2.2E+3	9.1E+1	1.0E+3	3.4E+2	3.0E+3
Occupation, dump site	Raw	[m^{2}yr]		X			1.4E+4	–1.2E+2	1.7E+2	5.7E+1	1.4E+4
Occupation, mineral extraction site	Raw	[m^{2}yr]		X			6.4E+3	–2.2E+4	4.8E+4	1.6E+4	1.7E+4
Occupation, traffic area, road network	Raw	[m^{2}yr]		X			9.0E+3	–2.9E+2	7.2E+2	2.4E+2	9.2E+3
Oil, crude, in ground	Raw	[kg]				X	1.1E+5	2.6E+3	4.0E+4	1.3E+4	1.4E+5
Particulates, < 2.5 µm	Air	[kg]	X				1.5E+2	–8.4E+0	6.9E+1	2.3E+1	1.8E+2
Particulates, > 10 µm	Air	[kg]	X				9.5E+1	–2.0E+1	6.3E+1	2.1E+1	1.2E+2
Particulates, > 2.5 µm, and < 10 µm	Air	[kg]	X				4.7E+1	–1.4E+1	3.3E+1	1.1E+1	5.6E+1
Sulfur dioxide	Air	[kg]	X				3.9E+2	–2.3E+1	1.9E+2	6.1E+1	4.9E+2
Uranium, in ground	Raw	[kg]				X	4.3E-1	–7.7E-1	6.7E-1	2.2E-1	9.9E-2
Zinc	Air	[kg]		X			3.8E-1	–1.5E-1	2.9E-1	9.5E-2	4.2E-1
Zinc	Soil	[kg]		X			8.6E-1	–1.2E-2	4.7E-1	1.6E-1	1.2E+0
Normalised damages (pers*yr)											
Human Health (HH)							5.4E+1	–1.3E+0	2.6E+1	8.6E+0	7.0E+1
Ecosystem Quality (EQ)							8.1E+0	–2.0E+0	6.7E+0	2.2E+0	1.1E+1
Climate Change (CC)							2.6E+1	–6.0E-1	1.3E+1	4.3E+0	3.4E+1
Resources (R)							3.8E+1	–2.4E+0	1.6E+1	5.3E+0	4.7E+1

[a] HH=Human health, EQ=Ecosystem quality, CC=climate change, R=Resources

4.4 Total impacts for ALCA

Total normalised damages for the ALCA are presented in **Fig. 3**. It should be remembered that there is much uncertainty in the model, especially for the calculation of primary impacts. For human health and ecosystem quality damages, the impacts of EM are greater by a factor of 3 and 18, respectively, due to residual site contamination. On the other hand, for damages to climate change and resources which do not have a 'primary impact' component, the impacts of BR are greater by factors of 34 and 42, respectively. These results show important trade-off between primary and secondary impacts and between damage categories, so that weighting of these damage scores will have a preponderant role in determining the preferable option.



Legend: HH=Human health, EQ=Ecosystem quality, CC=Climate change, R=Resources

Fig. 2: Contribution to impacts of development and occupation, damage level indicators

4.5 Total impacts for CLCA

The sum of incurred and avoided primary, secondary and tertiary potential impacts yields a measure of the total envi-

Table 14: LCIA results for functionally equivalent developments, development and occupation (40 years) phases, normalised damages level (pers*yr)

Damage	Tracked site	Urban sites	Suburban sites
Human Health	3.2E+2	3.8E+2	1.1E+3
Ecosystem Quality	8.6E+1	1.2E+2	3.3E+2
Climate Change	2.6E+2	3.0E+2	9.2E+2
Resources	2.2E+2	2.7E+2	9.0E+2

Table 13: Comparison of CLCI results for functionally equivalent residential developments

Elementary flow		**[unit]**	**Assoc. damage categories** [a]				**Tracked site**		**Avoided urban sites**		**Avoided suburban sites**	
			HH	**EQ**	**CC**	**R**	**Develop-ment**	**Occupation (per year)**	**Develop-ment**	**Occupation (per year)**	**Develop-ment**	**Occupation (per year)**
Aluminum	Air	[kg]		X			3.5E+0	9.7E-1	3.5E+0	1.1E+0	8.2E+0	3.4E+0
Aluminum	Water	[kg]		X			1.4E+1	9.0E+0	1.4E+1	1.1E+1	3.3E+1	3.4E+1
Aluminum	Soil	[kg]		X			9.2E-2	3.8E-1	9.2E-2	4.8E-1	2.2E-1	1.6E+0
Arsenic, ion	Water	[kg]	X				1.1E-1	6.4E-2	1.1E-1	7.9E-2	2.6E-1	2.6E-1
Carbon dioxide, biogenic	Air	[kg]			X		6.8E+2	1.0E+4	6.8E+2	1.0E+4	1.6E+3	1.4E+4
Carbon dioxide, fossil	Air	[kg]			X		4.5E+4	5.1E+4	4.5E+4	6.2E+4	1.1E+5	2.0E+5
Carbon monoxide, fossil	Air	[kg]	X				1.6E+2	1.4E+3	1.6E+2	1.8E+3	3.7E+2	6.3E+3
Copper	Soil	[kg]		X			4.1E-1	9.7E-3	4.1E-1	1.2E-2	9.6E-1	4.2E-2
Gas, natural, in ground	Raw	[m^3]				X	3.7E+3	1.8E+3	3.7E+3	2.2E+3	8.7E+3	7.3E+3
Nitrogen oxides	Air	[kg]	X	X			1.6E+2	2.0E+2	1.6E+2	2.5E+2	3.8E+2	8.1E+2
Occupation, arable	Raw	[m^2yr]		X			8.1E-11	-3.4E-10	8.1E-11	–2.5E-10	–1.1E+5	–5.6E+4
Occupation, construction site	Raw	[m^2yr]		X			*2.0E+4* [b]	4.3E+0	2.0E+4	4.8E+0	1.1E+5	1.2E+1
Occupation, industrial area, vegetation	Raw	[m^2yr]		X			*–2.0E+4* [b]	*–1.0E+4* [b]	–2.0E+4	–1.0E+4	6.7E+1	3.9E+1
Occupation, traffic area, road network	Raw	[m^2yr]		X			1.2E+2	1.1E+3	1.2E+2	1.4E+3	2.7E+2	5.0E+3
Occupation, urban, continuously built	Raw	[m^2yr]		X			0.0E+0	*1.0E+4* [b]	0.0E+0	1.0E+4	0.0E+0	0.0E+0
Occupation, urban, discontinuously built	Raw	[m^2yr]		X			1.9E-3	8.2E-3	1.9E-3	1.0E-2	4.4E-3	5.6E+4
Oil, crude, in ground	Raw	[kg]				X	7.6E+3	1.4E+4	7.6E+3	1.7E+4	1.8E+4	5.8E+4
Particulates, < 2.5 µm	Air	[kg]	X				2.1E+1	1.6E+1	2.1E+1	1.9E+1	4.8E+1	5.6E+1
Particulates, > 10 µm	Air	[kg]	X				4.2E+1	4.4E+1	4.2E+1	5.0E+1	9.9E+1	1.3E+2
Particulates, > 2.5 µm, and < 10 µm	Air	[kg]	X				3.6E+1	2.0E+1	3.6E+1	2.2E+1	8.5E+1	5.1E+1
Sulfur dioxide	Air	[kg]	X				1.3E+2	1.1E+2	1.3E+2	1.3E+2	3.1E+2	4.4E+2
Uranium, in ground	Raw	[kg]				X	1.8E-1	1.9E-1	1.8E-1	2.3E-1	4.3E-1	7.4E-1
Zinc	Air	[kg]		X			2.5E-1	1.6E-1	2.5E-1	2.0E-1	5.9E-1	6.8E-1
Zinc	Soil	[kg]		X			3.1E-2	3.6E-1	3.1E-2	4.6E-1	7.3E-2	1.6E+0

[a] HH=Human health, EQ=Ecosystem quality, CC=climate change, R=Resources
[b] Tracked site land use figures in italics are shown for illustrative purposes only but are actually accounted for in primary impacts

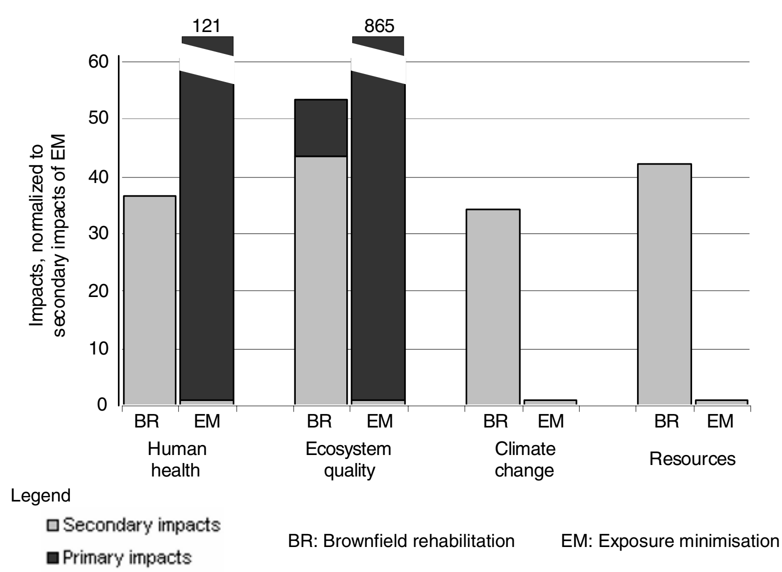


Fig. 3: Total damages for the ALCA, normalised to secondary impacts of the default option

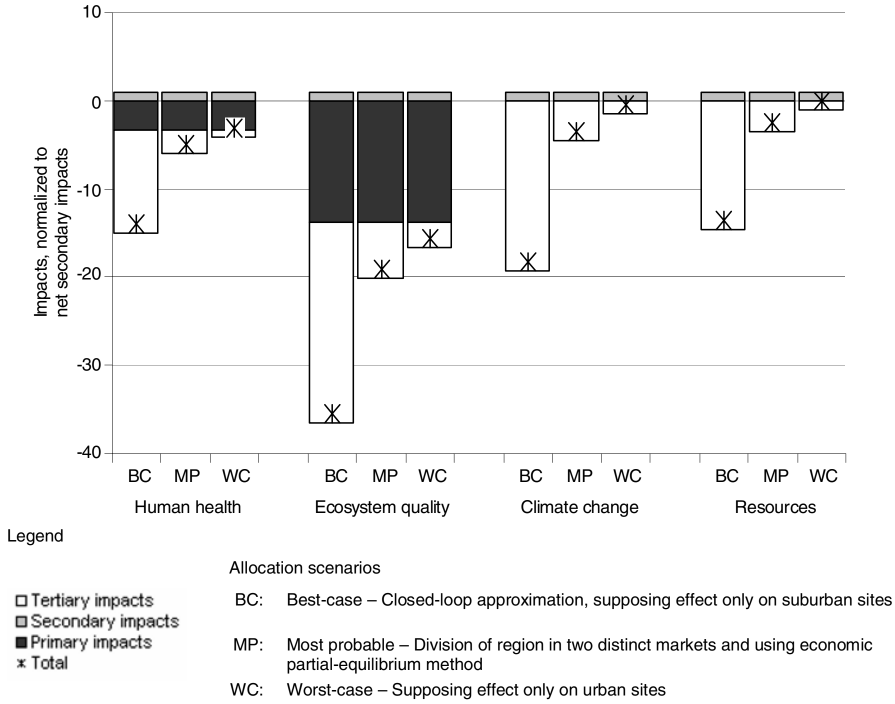


Fig. 4: CLCA results for three allocation scenarios, normalised to secondary impacts

ronmental consequences of BR. The sums are shown for the four damage categories and the three allocation scenarios in **Fig. 4**. For the best-case allocation scenario, (negative) tertiary impacts are larger than (positive) secondary impacts by a factor of 12 to 23, indicating that BR is an environmentally sound option even without considering primary impacts. The results for the most probable allocation scenario also indicates that BR is environmentally sound, with tertiary impacts superior to secondary impact by factors of 3 to 6. For the worst-case allocation scenario, secondary and tertiary impacts are of the same order of magnitude and nearly cancel each other out for all damage categories except ecosystem, quality. For this last, tertiary impacts for the worst case scenario are about three times secondary impacts. When primary impacts are considered, all three allocation procedures favour BR.

Even though they do not contribute significantly to ecosystem quality damages, land occupation midpoint impacts are discussed here because they do not follow the general trend observed for other impacts. **Table 15** presents the land occupation inventory results (area*time of occupation) strictly for the tracked site and for sites where construction was avoided. Suburban residential development is assumed to displace farmland. In all allocation scenarios affecting suburban sites, this ultimately results in farmland being conserved. Although this would intuitively seem beneficial, **Table 16** shows that the contrary is true, because the ensuing residential occupation has lower impacts than the farmland it replaces

Table 16: Land occupation damages, considering only tracked and avoided sites (PDF*m²yr)

	Best case	Most probable	Worst case
Greenfield considered farmland	5.8E+5	1.0E+5	0.0E+0
Greenfield considered forest	–1.9E+6	–3.3E+5	0.0E+0

Table 15: Total land occupation inventory, considering only tracked and avoided sites (t=44 years)

Land occupation type	Corine proxy	Damage factor	Inventory result per allocation scenario		
		[PDF*m²yr/ m²yr]	Best case m²yr	Most probable m²yr	Worst case m²yr
Site being remediated [a]	Construction site	8.4E-1	2.0E+4	2.0E+4	2.0E+4
Construction site	Construction site	8.4E-1	–9.1E+4	–1.6E+4	0.0E+0
Brownfield	Industrial site, vegetation	8.4E-1	–4.3E+5	–4.3E+5	–4.3E+5
Suburban residential	Urban, discontinuously built	9.6E-1	–2.2E+6	–4.0E+5	0.0E+0
Farmland	Arable	1.2E+0	2.3E+6	4.2E+5	0.0E+0
Vacant site	Industrial site, vegetation	8.4E-1	0.0E+0	3.5E+5	4.2E+5
Urban residential	Urban, continuously built	1.2E+0	4.0E+5	7.1E+4	0.0E+0

[a] Site being remediated is for both the incurred brownfield rehabilitation (2 yr) and the avoided exposure minimisation (1 yr)

Table 17: Payback periods of BR for damage categories and for three allocation scenarios

	Considering primary impacts of contamination			Excluding primary impacts of contamination		
Damage category	Best-case	Most probable	Worst case	Best-case	Most probable	Worst case
Human health	Rehabilitation	Rehabilitation	Rehabilitation	3 yr of occ.	15 yr of occ.	47 yr of occ.
Ecosystem quality	Rehabilitation	Rehabilitation	Rehabilitation	2 yr of occ.	8 yr of occ.	20 yr of occ.
Climate change	2 yr of occ.	9 yr of occ.	29 yr of occ.	2 yr of occ.	9 yr of occ.	29 yr of occ.
Resources	2 yr of occ.	12 yr of occ.	36 yr of occ.	2 yr of occ.	12 yr of occ.	36 yr of occ.

(this explains the negative contribution to ecosystem quality in Fig. 2). This is because IMPACT 2002+ measures land occupation impacts as a function of biodiversity, and that discontinuous urban land has higher biodiversity than farmland. Had the indicator rather been based on net primary production (NPP), farmland may have been the preferred land occupation type, in which case this out-of-trend result would not have surfaced. Also, Table 16 shows that, had the affected greenfields been considered to initially be forest rather than farmland, these avoided developments would also have been considered beneficial. Of course, no change is seen for worst-case allocation scenario, which does not involve any greenfields.

Since redeveloping and reoccupying the site is environmentally beneficial, it is possible to consider secondary impacts as an initial investment and to calculate the payback period, i.e. the number of years it takes for BR to be environmentally profitable. Payback periods are presented in **Table 17** with and without the benefits of avoided soil contamination. When these benefits are considered, payback for human health and ecosystem quality damages is immediate. When avoided soil contamination is excluded, payback periods for these two categories are still under 3 years of occupation for the best case scenario and 15 years of occupation for the most probable scenario. All calculated payback periods are under the 40 year time horizon except for human health damages in the worst case allocation scenario (47 years).

4.5 Sensitivity analyses for the CLCA

Annulment of the ceteris paribus assumption: The effects on the life-cycle of other sites were calculated based on a ceteris paribus assumption by which the total regional demand for housing services was considered unaffected. A sensitivity analysis was conducted for which this assumption was annulled. A partial-equilibrium model is again used, but this time the directly affected market is defined as the whole region rather than the urban area only. The same values of price elasticity are used. The total regional demand is therefore assumed to increase by a quantity that corresponds to 17.8% of the residential services provided at the tracked site. If only suburban sites are considered affected (**Fig. 5a**), annulling the ceteris paribus assumption reduces tertiary impacts by about 25%, but BR remains beneficial. If only urban sites are considered affected (**Fig. 5b**), however, tertiary impacts become insignificant for all but ecosystem quality damages, and the conclusions are about the same as those that can be derived from the ALCA model.

Perturbation analysis: A perturbation analysis was carried out on 26 continuous parameters. The magnitude of the perturbation is +1%. The effects on the unweighted sum of normalised damages are presented in **Table 18**. Effects at least of the same order of magnitude as the perturbation (>1%) are darkly shaded, and effects greater than one tenth ofe the perturbation (>–.1%) are lightly shaded. **Fig. 6** presents the effects of the perturbation of the five most sensi-

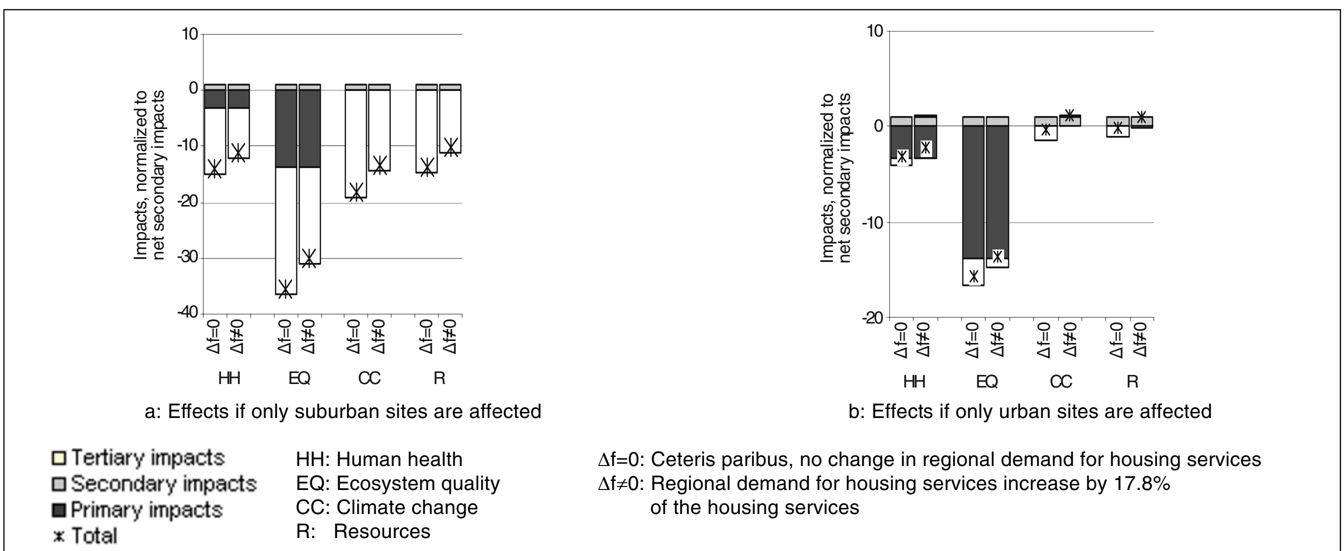


Fig. 5: Effect of annulling the ceteris paribus assumption on the demand for regional housing services

Table 18: Results of perturbation analysis for continuous parameters (unweighted sum of normalised damages)

Perturbed continuous parameters		Effect on sum of unweighted normalised damages [a] Allocation scenario Best case	Most probable	Worst case
Parameters affecting primary impacts				
1	1% increase in PHC concentration	–4.8E-6	–1.6E-5	–3.1E-5
2	1% increase in metal ion concentration	–6.6E-4	–2.2E-3	–4.3E-3
3	1% increase in PAH concentration	–1.0E-3	–3.3E-3	–6.6E-3
Parameters affecting secondary impacts				
4	1% increase in <B soil volume	9.1E-7	3.0E-6	5.9E-6
5	1% increase in BC soil volume	2.2E-4	7.1E-4	1.4E-3
6	1% increase in >C soil volume	1.2E-4	3.9E-4	7.8E-4
7	1% increase in dry solid waste volume	3.6E-5	1.2E-4	2.4E-4
8	1% increase in slag (special waste) volume	4.1E-6	1.4E-5	2.7E-5
9	1% increase in slag (solid waste) volume	1.1E-4	3.6E-4	7.1E-4
10	1% increase in bituminous concrete volume	–3.1E-6	–1.0E-5	–2.0E-5
11	1% increase in cement concrete volume	–2.1E-5	–7.0E-5	–1.4E-4
12	1% increase in loss of elevation of site after backfill (reduces backfill volume)	1.4E-4	4.5E-4	9.0E-4
13	1% increase in total offsite transportation, dig and haul phase (tkm)	1.4E-4	4.8E-4	9.5E-4
14	1% increase in total offsite transportation, backfill phase (tkm)	1.3E-4	4.4E-4	8.8E-4
15	1% increase in total offsite transportation, exposure minimisation (tkm)	–1.3E-4	–4.4E-4	–8.8E-4
16	1% increase in soil cover for exposure minimisation option	–7.8E-5	–2.6E-4	–5.1E-4
Parameters affecting tertiary impacts				
17	1% increase in population densities on the tracked site	–9.2E-3	–7.6E-3	–5.4E-3
18	1% increase in population densities on affected urban sites	–	3.7E-4	8.9E-4
19	1% increase in population densities on affected suburban sites	1.1E-4	6.3E-5	–
20	1% increase in floor space for attached single-family dwellings	6.3E-4	3.7E-4	1.0E-10
21	1% increase in floor space for detached single-family dwellings	–8.5E-4	–5.0E-4	–
22	1% increase in distance travelled by residents on the tracked site	2.5E-3	8.4E-3	1.7E-2
23	1% increase in distance travelled by residents on affected urban sites	–	–8.7E-3	–2.1E-2
24	1% increase in distance travelled by residents on affected suburban sites	–1.1E-2	–6.7E-3	–
25	1% increase in time of occupation	–9.1E-3	–7.3E-3	–4.7E-3
26	1% increase in car efficiency	6.9E-3	5.5E-3	3.5E-3

[a] Effects are calculated as $\frac{I_{perturbed} - I_{baseline}}{|I_{baseline}|}$, where

$I_{baseline}$ is the unweighted sum of normalised damages for the unperturbed model, and
$I_{perturbed}$ is the unweighted sum of normalised damages for the perturbed model

tive parameters on each type of damage. For all allocation scenarios, parameters directly or indirectly affecting residents' transport are clearly the most sensitive. For the worst case scenario, all parameters are much more sensitive, showing the precarious balance between secondary and tertiary impacts.

Alternative model assumptions: The influence of two potentially significant modeling choices in the CLCA is examined. The results of using alternative choices are presented in **Fig. 7**, normalised to the baseline model.

(1) Long-term emissions: In the baseline model, future emissions of landfilled/contained contaminants are excluded. If all contaminants are assumed to be emitted, primary benefits are annulled. If it is instead assumed that only metals will leach (biodegradation of other contaminants), primary benefits are very small. In both cases, BR of urban sites remains the preferred option if suburban sites are affected. In the ALCA, however, these alternative models would strongly support EM over BR.

(2) Residential energy: Two residential heating types (electricity, gas) and three marginal electricity production types (hydro, wind and gas) are considered, giving rise to six distinct scenarios, one of which (electric heating, hydroelectricity) is the baseline model. All energy inventory data for these was taken from the ecoinvent 1.2 database [38]. For all allocation scenarios which involve avoided suburban developments, alternative energy scenarios either have no

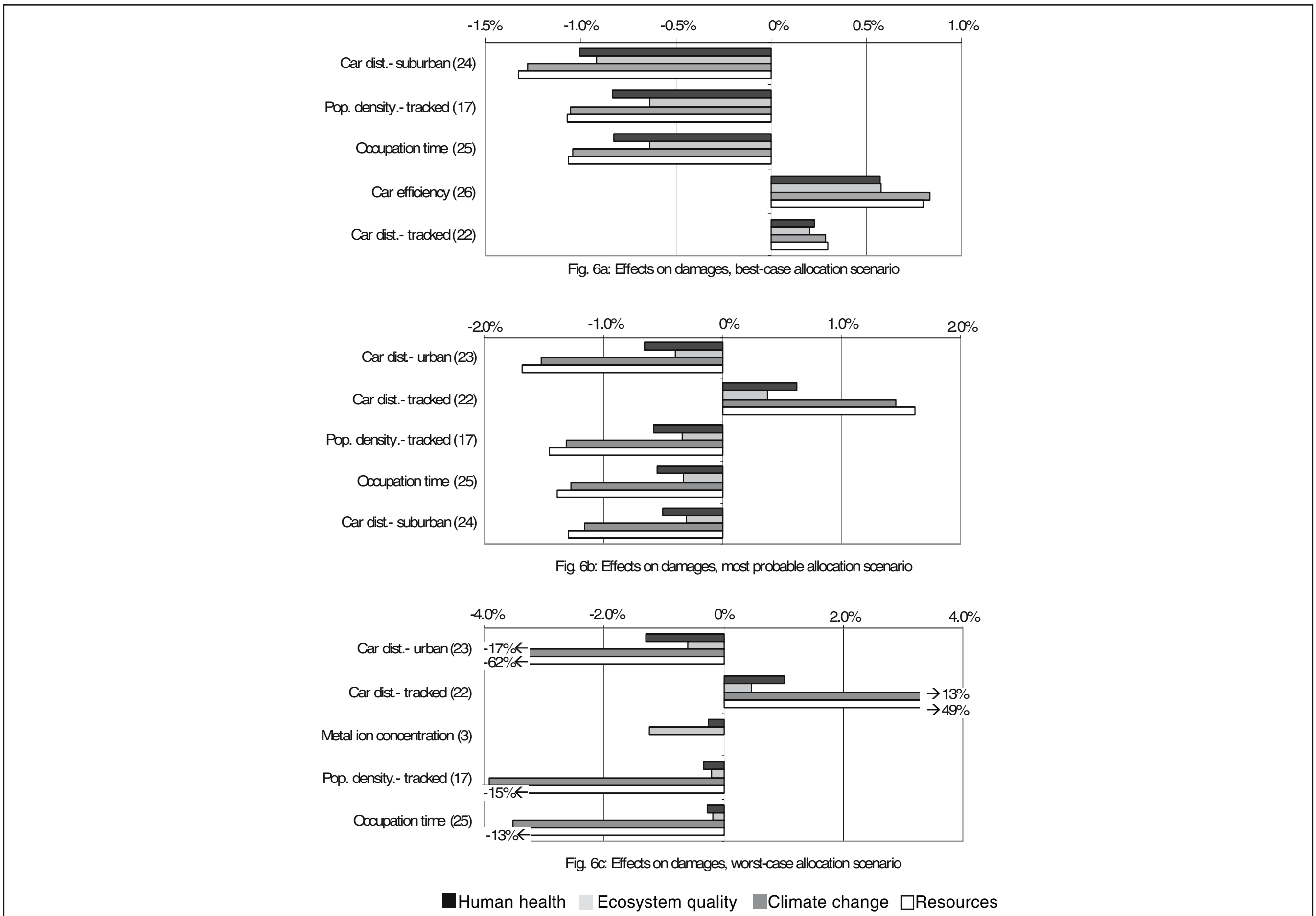


Fig. 6: Effects on damages of a +1% perturbation of most sensitive parameters

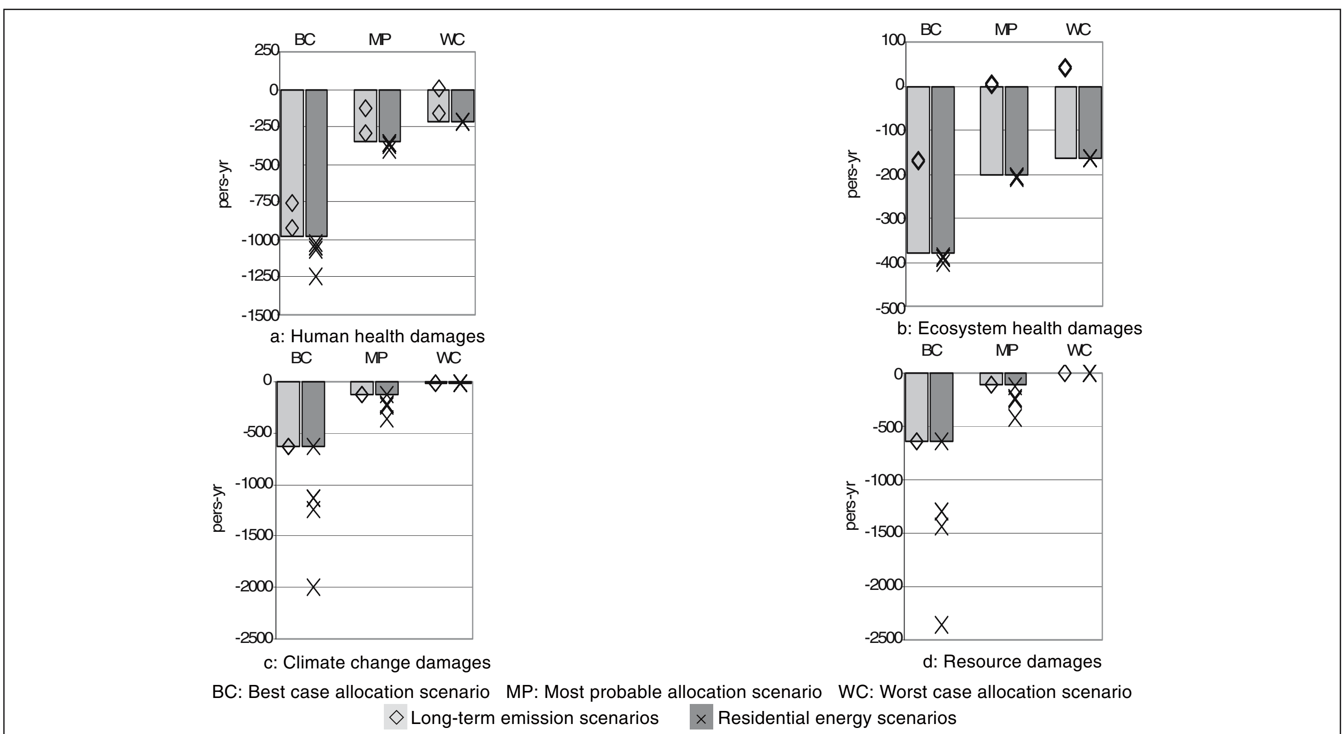


Fig. 7: Scenario analysis for selected discrete model parameters in the CLCA

significant effect (e.g. electric, wind) or increase the tertiary benefits of BR. This is especially true for climatic changes and resources damages for all energy scenarios that based on natural gas. The baseline model was the most conservative alternative.

5 Conclusions

The decision evaluated in this paper dealt with three linked issues regarding the management of the brownfield: (1) its state, (2) its fate and (3) the means to change both these factors. The ALCA did not cover the issue of the site's fate. It showed that changes to the site's contamination dominated impacts related to the site's state. Its overall results, however, did not allow distinguishing easily whether it was better to completely remove these contaminants through rehabilitation or to simply minimise exposure to them, because of trade-offs between primary and secondary impacts.

The CLCA, for its part, covered all three issues. The site's fate clearly dominated overall results for all allocation scenarios that considered some effect on suburban sites. The most significant difference between suburban sites and the tracked site was resident's transport distances. The location of the brownfield is therefore crucial to the environmental performance of BR. Since the ratio between urban and suburban affected sites is key to determine the environmental value of BR, more sophisticated tools from the field of spatial-planning could be more recommendable to determine the most probable ratio, instead of the economic partial-equilibrium model proposed.

For decision contexts where the final state and fate of the site are predetermined, only secondary impacts are relevant. The use of ALCA and CLCA to calculate these secondary impacts only did not yield significantly different results.

6 Recommendations and Perspectives

This case study adds to the extensive literature on the advantages of the active reintegration of brownfields in the economy, although significant factors that can undermine this advantage are identified (e.g., location of the brownfield, proper identification of affected sites). It also shows how CLCA can quantify these advantages, possibly useful for, e.g., municipalities considering brownfield redevelopment as a means to meet carbon emission targets.

Given the dominance of tertiary impacts, it may be tempting to conclude that, from an environmental point of view, the decisions regarding the reuse of the site should be made separately and prior to decisions regarding how to allow this change in fate, since improvements made in the rehabilitation phase will only allow comparatively minor reductions in overall impacts. However, since tertiary impacts are sensitive to key parameters that can differ greatly from site to site (or from region to region), this generalisation is not recommended. Rather, it is recommended here that all three aspects of brownfield management should be considered jointly when deciding how to manage a brownfield.

The framework developed in the first article proved to be useful for decisions regarding the residential redevelopment of single brownfields. It is suggested here that it can be adapted for other applications. First, other types of reuse, such as commercial or industrial, could be assessed. The tertiary impacts of a commercial redevelopment would intuitively be sensitive to changes in travel distances of the potentially affected customers. Those of an industrial redevelopment would probably depend on how distances from raw materials, workforce and markets are affected. Although primary data gathering would differ greatly, the overall methodology could remain the same.

The methodology may also be useful for stakeholders called to choose how to allocate resources for rehabilitation to a set of brownfields under its control, for example a company owning many brownfields or an organisation attributing limited grants to brownfield owners for intervention. The CLCA of the management of these different sites will yield different primary, secondary and tertiary impacts because of different initial states, applicable remediation technologies, site contexts and location. The basis of comparison should be changed for this type of analysis to cost (e.g. impacts/dollar spent).

Finally, decisions regarding the risk-based criteria for land occupations may also profit from this methodology. For example, the policy decision to impose more stringent criteria will result in a number of sites that were initially redevelopable to be reclassified as brownfields. This reduces available land, pushes development onto greenfields and therefore probably has important tertiary impacts. Secondary impacts (more interventions will be done) and primary impacts (exposure to contaminants is reduced) are also likely to be affected. The magnitude of the perturbation on land use will probably be too large to be considered marginal, however. The scope may have to include long-term capacity adjustment, e.g. large-scale construction of municipal infrastructure to accommodate for developments in periurban areas. It is not clear whether a functional unit would be appropriate here, nor if the resulting assessment can truly be called a life-cycle assessment.

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